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A solution for high damping constants in sands

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ABSTRACT: Previous dynamic pile testing has occasionally revealed cases of apparent and unexpected high damping in sandy soils normally thought to exhibit small velocity dependent damping forces. This resulted in much harder than expected pile driving and also unexpectedly low static capacities. While these cases were observed during the dynamic testing to be unusual, no satisfactory solution was previously available and correlations with static tests were often disappointing.

Recent efforts have produced a new soil model which allows more realistic solutions and yields satisfactory capacity estimates. The mechanism, model and case histories are discussed which clearly demonstrate the appropriateness of this solution.

1 INTRODUCTION

Unexpected for sandy soils, difficulties have been experienced at a few piling sites in modeling the soil response by CAPWAP^{TM} using the standard Smith (1960) soil model. Solutions show unusually high Smith shaft damping factors, resulting in capacity predictions which are low compared with static tests. Recent efforts have produced a new soil model which yields satisfactory CAPWAP capacity estimates. It is important that the character of this dynamic response of these unusual conditions be understood and identified so that future correlations can be improved.

The cases presented here clearly distinguish themselves from those where previous dynamic pile testing has occasionally revealed unexpected high damping in sandy soils (Thompson, Goble 1988). In those cases high damping in the presence of both high blow counts and unexpectedly low static capacities were correctly identified by the CAPWAP analysis with the standard soil model. In the above referenced work, involving both concrete and steel piles driven by both air and diesel hammers, the soils all exhibited high shaft damping and were also water borne deposits.

2 CASE HISTORY 1

The 600mm square section 32m long prestressed pile was driven to 30m penetration at about 30 blows per meter for the last 9m of driving. The water borne, saturated soils are wet dark grey organic silts of very low strength in the upper 9m, and underlain by wet grey fine silty sand (SPT N value per 300 mm of 30 to 50+).

Six days later, the pile was redriven at about 4mm per blow with a Delmag D46 hammer. Figure 1 indicates significant shaft friction by the separation of the force and velocity curves prior to time 2L/c (L is the pile length and c the stress wave speed). However, these two signals after 2L/c indicate relatively low resistance as they are not then widely separated.

CAPWAP Rausche (1972) at the beginning of restrike (BOR) indicated a capacity of 1265kN (compared with a 750 kN design load) and unusually high Smith damping constants of 1.38 s/m for the shaft and 57.66 s/m for the toe! The Smith toe damping value is particularly large as a result of low toe bearing. An end of redrive blow (EOR) was also analyzed by CAPWAP resulting in only 1130kN capacity, including 775kN toe resistance, and the Smith shaft damping value was now an unreasonable 5.25 s/m. Apparently the shaft friction was predominate in the early blow while the toe resistance was predominate in the EOR case.

This pile was then loaded statically five days after the restrike to a maximum applied load of 2270kN. It was suggested that the additional five waiting days between the six day restrike and the static test allowed further capacity increase. However, since the silty soil has fairly high permeability, such large capacity increases due to pore pressure changes would be highly unusual.

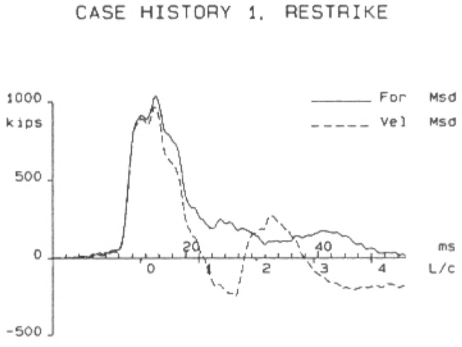


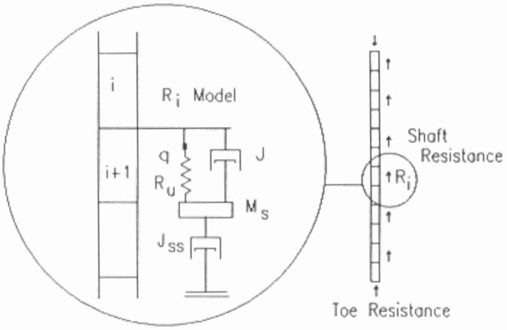
Fig. 1 Dynamic measurements for case history 1
1 kip = 4.46 kN

3 NEW SOIL MODEL

The pile forces due to impact result in downward pile motion which creates passive soil forces resisting pile penetration. The basic soil model (Smith 1960) assumes that the energy dissipation associated with the soil resistance occurs in a slip layer, i.e., in the pile soil interface and that the surrounding space consists of rigid soil. However, energy originating in the hammer is clearly dissipated in the soil as pile driving observers can feel the effects of the moving ground. Several factors such as soil type, pile shape and volume, and pile shaft smoothness affect the magnitude of these soil vibrations. If the pile cleanly slips relative to the soil, this energy loss can be easily handled by the traditional Smith model, as happens in most driven pile projects analyzed. However, in cases where the surrounding soil moves substantially, a new model is needed. Figure 2 shows a new CAPWAP soil model, employed whenever the Smith damping factors exceed values of 1.3 s/m and driving resistance is moderate to hard. This new model has produced results in which correlated well with static tests.

This new "soil support dashpot" or radiation damping model is separated from the standard Smith soil model (pile soil interface) by a mass representing a volume of moving soil. As the soil resistance builds at the pile soil interface, the soil mass begins to move but at a delayed rate because of its inertia. The mass movement rate is also dependent upon the "stiffness" of the soil support dashpot.

The BOR blow was analyzed again using the new soil model and a solution with an equivalently good match quality was obtained, but with a capacity matching the static result (Figure 3) and reasonable Smith damping factors. It is suggested that the apparent shaft friction (about half the total capacity) breaks down during the blow due to radiation of energy into soil mass surrounding the pile.



Standard Smith soil model
  Ru - Elastic plastic static resistance
  J - Smith (or Viscous) damper
Radiation damper model
  Ms - Mass of "moving" soil
  Jss - Radiation damper

Fig. 2 Soil model with radiation damper

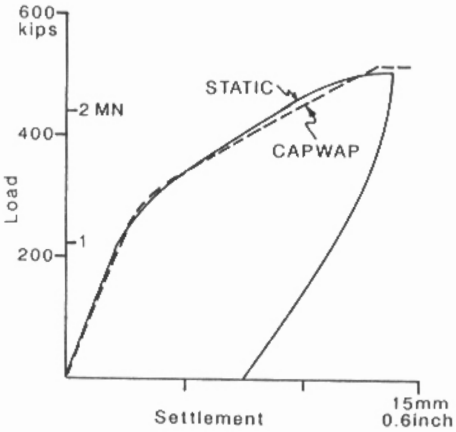


Fig. 3 CAPWAP simulation and measured static load settlement curves for case history 1

4 CASE HISTORY 2

The project site was in the Coastal Lowlands and Alluvial - Deltaic Plain of the Mobile River. The area is underlain by unconsolidated alluvial deposits of recent age with locally occurring swamp areas. These alluvial deposits consist of fine-to-coarse grained sand and sandy clay with locally high organic content.

Depth	Description	SPT N Value/300mm
0 - 11m	silty, sandy	0 - 10
11 - 15m	clay	9 - 13
15 - 18m	silty sand	35
18 - 24m	clayey sand	31 - (50 per 100mm)
24 - 26m	silty sand sand	50 per 100mm

The groundwater table was at a depth of 0.6m. Two sand layers with hydrostatic pressure were noted at depths of 8 and 24m.

Records from six prestressed concrete piles were analyzed (DiMaggio 1991). CT1 and CT2 were 450mm solid section piles with penetrations of 20 and 23m, respectively. CT3 and CT4 were 600mm square piles with 260mm diameter void but 1 meter solid sections at top and bottom. They also had penetrations of 20 and 23m, respectively. CT5 and CT6 were 900mm square piles with 570mm diameter void (solid 1 meter at top and bottom) and penetrations of 22 and 25m, respectively. All piles were tested during driving and later by restrike after both short (1 to 3 days) and longer (8 to 11 days) wait periods with respect to the end of driving (EOD). A Kobe K25 hammer was used for CT1, CT2, CT3 and CT4 and a Delmag D62-22 for CT5 and CT6. Both compressive and tensile driving stresses approached or exceeded recommended allowable values. Although pile damage was not apparent, careful control of hammer fuel settings and pile cushion thickness was necessary. Finally these piles were tested statically 17 to 22 days after EOD.

Table 1. Site 2 capacities from different methods

Pile	Design[1] Load kN	Dynamic[1] Formula kN	Static[2] Analysis kN	CAPWAP[2] kN	Static[2] Test kN
CT1,EOD[3]					
2 Day		1720		913	
11 Day		2560		1145	
21 Day	2530	3140	4850	1702	1666[4] 1915[5]
CT2,EOD		1630		1907	
11 Day		3140		2668	
22 Day	2530		6720		2540[4] 2673[5]
CT3,EOD		1700		2615	
8 Day		4180			
22 Day	3820		7420		2869[4] 3118[5]
CT4,EOD		3310		1987	
1 Day		3170		2691	
10 Day		Refusal		3617	
22 Day	3820		11,160		3724[4] 4009[5]
CT5,EOD		6890		2949	
6 Day		5390		4210	
20 Day	7000		12,870		4900[4] 5345[5]
CT6,EOD		7430		3287	
3 Day		8600		4994	
17 Day	7000		30,744		6905[4] 6905[5]

1. Allowable load (for minimum safety factor of 2.0, failure load should be at least twice the allowable value)
2. Ultimate or failure load
3. Number of days after end of drive (EOD)
4. Davisson limit load
5. Plunging load

Table 1 compares several capacity prediction methods for all test piles. Both end of driving and beginning of restrike conditions were evaluated and compared with static loading test results. Capacity results were calculated by static analysis, driving formula (Engineering News), and CAPWAP analysis of the dynamic measurements. The static analyses (Tomlinson and Nordlund methods) were performed using the Federal Highway Administration computer program SPILE. Static analysis (Table 1) grossly over estimated pile capacities as the average prediction was 2.42 times higher than the maximum applied test load, probably because of the fine soil grain fraction and organic components of the soil matrix. The Engineering News pile driving formula also grossly over-predicted pile capacity by a factor of over 2 for both end of drive and beginning of restrike conditions.

5 DYNAMIC TEST RESULTS FOR CASE HISTORY 2

The dynamic behavior of the pile (Figure 4) during the first 2L/c again shows high shaft resistance effects (difference between forced proportional velocity before 2 L/c) which quickly disappears during the blow. The soil along the shaft exhibits temporary resistance behavior rather than shearing at the pile soil interface; the soil then seems to be moving away from the pile motion induced load. This reduces the soil resistance effects approvement in the pile top records.

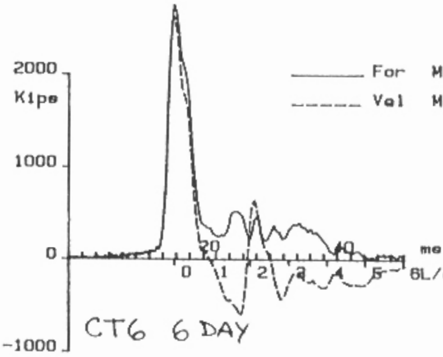


Fig. 4 Dynamic measurements for case history, site 2

It is then not surprising that CAPWAP solutions using the classic Smith soil model produced low calculated static resistance values and high Smith damping factors. For example, for the traditional Smith model on CT4, the 2900kN capacity solution for the 10 day restrike does not agree with the static test (3724kN) and the Smith shaft damping factor of 1.80 s/m is high compared with normal experience. Using the new radiation damper model, the CAPWAP capacity of 3617kN is in good agreement with the static test result and the Smith skin damping constant of 1.19 s/m was within the normally accepted range of up to 1.3 s/m. While it is clear that this model produces better capacity correlations, attempts were made to find the minimum damper value (greatest soil motion effect) still giving a good match quality to estimate the upper bound of the capacity. This highest result of 3795kN falls between the Davisson limit of 3724kN and the plunging load of 4009kN.

Higher radiation damper values which are more stiff (less soil motion) were observed at EOD. Lower values (more soil motion) occurred as wait times increased, perhaps due to the pile and soil bonding into a more cohesive unit as pore water pressures dissipated and effective soil stresses increased.

The CAPWAP results with the radiation damping model are summarized for all piles in Table 2 and clearly demonstrates shaft friction and bearing capacity increases as a function of time (set-up). The large capacity increases with time (set-up) are considered unusual for sandy soil. The shape of all static tests, however, had a plunging type failure associated with finer grain soils. The hydrostatic pressure and excess pore pressures (lower effective stresses) generated during driving contributed to the observed behavior. The fine grain content seems to control the permeability preventing normal rapid drainage conditions associated with clean sands. A large toe quake also was observed during driving and was lower on restrike after reduction in pore pressures; this is consistent with previous experience of piles driven into saturated soils (Likins 1983).

The ratio of capacity at various test time intervals to the plunging static load appears as a linear function of log

Table 2. Summary of CAPWAP results, site 2

Pile Data	Set	Stroke	Smith Damping Skin	Toe	Unit Frict.	Ultimate Capacity
	mm/bl	m	s/m	s/m	kPa	kN
CT1						
EOD	17.0	1.74	.77	.40	10.1	913
2 Day	17.0	1.77	1.20	1.20	20.1	1145
11 Day	6.3	2.68	1.06	1.20	33.5	1702
21 Day	Static Test					1666[1]
						1915[2]
CT2						
EOD	7.3	1.92	.71	.33	18.7	1907
11 Day	5.0	2.68	1.07	1.06	45.5	2668
22 Day	Static Test					2540[1]
						2673[2]
CT3						
EOD	9.0	2.20	1.08	.60	15.8	1515
8 Day	2.8	2.68	1.30	1.01	38.8	2615
22 Day	Static Test					2869[1]
						3118[2]
CT4						
EOD	4.0	2.16	.97	.50	10.5	1987
1 Day	3.6	2.16	1.28	1.10	26.8	2691
10 Day	2.5	3.38	1.19	1.13	43.1	3617
22 Day	Static Test					3724[1]
						4009[2]
CT5						
EOD	3.3	3.32	.99	1.30	17.7	2949
6 Day	4.2	3.35	1.30	1.30	37.9	4210
20 Day	Static Test					4900[1]
						5345[2]
CT6						
EOD	2.9	3.26	1.24	1.25	20.6	3287
3 Day	2.5	3.35	1.21	1.21	39.3	4994
17 Day	Static Test					6905[1]
						6905[2]

1. Davisson limit load
2. Plunging load

time. The average capacity ratios for the five piles dynamically tested six or more days after the EOD to the plunging static load was 87 percent. Minimum wait periods of one week were therefore recommended for all future tests at this site.

6 CONCLUSIONS

In most cases the traditional Smith soil model adequately represents the dynamic soil behavior of impacted piles as evidenced by good correlation of CAPWAP results with static test loadings. Occasionally, however, the dynamic behavior does not fit the traditional solution and shows initially high shaft resistance followed by a rapid breakdown of resistance later in the blow producing high Smith damping constants and low CAPWAP static capacity predictions. Such behavior suggests that the soil is set into motion. In both test cases, the new radiation damping model, which simulates the motion of the soil surrounding the pile, produced good static/dynamic correlations with reasonable Smith damping constants.

Fortunately, these unusual soil conditions are encountered on relatively few project sites. They are observed primarily on displacement piles (or drilled shafts) installed in dense fine sands or silts which are also saturated and generally water borne.

It is suggested that the new radiation damping model not be used unless the Smith damping factors exceed as a minimum 0.8 s/m and that the maximum Smith damping factors be limited to at most 1.3 s/m to produce the best correlations with static tests. Bearing capacity confirmation by static tests is often recommended in these unusual soils; the dynamic test should be performed with similar wait times to the static tests to properly account for soil strength increases with time often present in such soils.

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